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# An Analog Echocardiogram for Estimating Ventricular Stroke Volume

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16. ABSTRACT

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Two conventional time-analog range-gated modules have been redesigned and synchronized with the initial transmit pulse of 1000 hz, for the purpose of simultaneously gating echocardiographic images of the anterior and posterior left ventricular walls. Each echocardiographic image boundary is selectively gated in the A-Mode and adjusted to a width exceeding the maximum wall motion. The gated echocardiographic boundary of each time-analog channel is processed by a Peak-attack envelope detector and a low-pass filter network to produce a D.C. analog signal corresponding to the motion of the left ventricular anterior and posterior wall. These analog signals serve as the basis for the estimation of ventricular stroke volume and the computation of cardiac output.

Pilot studies were conducted in six healthy male subjects to evaluate the feasibility of producing the analog signals equivalent to the echo image boundaries of the anterior and posterior left ventricular walls on a beat-by-beat basis. The results of these studies have shown a favorable comparison between the conventional echocardiographic analysis and estimation of stroke volume and cardiac output based on the analog method described here. These findings are encouraging and serve as a basis for continuing developments and studies to provide for automatic tracking of wall boundary echos and computational procedures through microprocessor techniques.

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# AN ANALOG ECHOCARDIOGRAM FOR ESTIMATING VENTRICULAR STROKE VOLUME

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## ABSTRACT

A multiple range-gated echocardiographic signal processor has been developed for the purpose of converting the complex ultrasonic image of the left ventricular anterior and posterior wall boundaries to equivalent analog signals as a means of estimating stroke volume and computing cardiac output.

Two conventional time-analog range-gated modules have been redesigned and synchronized with the initial transmit pulse of 1000 hz, for the purpose of simultaneously gating echocardiographic images of the anterior and posterior left ventricular walls. Each echocardiographic image boundary is selectively gated in the A-Mode and adjusted to a width exceeding the maximum wall motion. The gated echocardiographic boundary of each time-analog channel is processed by a fast-attack envelope detector and a low-pass filter network to produce a D.C. analog signal corresponding to the motion of the left ventricular anterior and posterior wall. These analog signals serve as the basis for the estimation of ventricular stroke volume and the computation of cardiac output.

Pilot studies were conducted in six healthy male subjects to evaluate the feasibility of producing the analog signals equivalent to the echo image boundaries of the anterior and posterior left ventricular walls on a beat-by-beat basis. The results of these studies have shown a favorable comparison between the conventional echographic analysis and estimation of stroke volume and cardiac output based on the analog method described here. These findings are encouraging and serve as a basis for continuing developments and studies to provide for automatic tracking of wall boundary echos and computational procedures through microprocessor techniques.



MS-15-031

## INTRODUCTION

Studies of dynamic ventricular geometry have yielded important information relative to the understanding of cardiac function and its performance. The non-invasive determination of ventricular volume, ejection fraction and myocardial contractility have served as a valuable resource in caring for cardiac patients(1) and as the basis for the development of sensitive health indicators resulting from air pollution exposure(2).

In the last decade imaging the heart and quantitation of ventricular stroke volume and cardiac output have been based on visual identification of cardiac structural boundaries through a variety of complex biomedical instrumentation systems including such techniques as; cineangiography(3), video-densitometry(4) and radioisotometry (5). While these systems provide a means for "visualizing" dynamic and pulsatile cardiac performance, they require procedures that are invasive and utilize material that present some hazard to the subject.

The development of echocardiography has, in the last five years, provided an alternative procedure for determining ventricular stroke volume and cardiac output non-invasively. The practical problems associated with the processing of non-invasive clinical echocardiographic boundary signals in the determination of changing cardiac geometry has been difficult. Usually interpretation and analysis of the displayed ultrasonic signals have been accomplished manually by outlining the boundaries of echo patterns from cardiac structures with a line drawing superimposed on the oscillographic tracing of the echo pattern in the M-Mode(6). This process is always time consuming and usually requires some arbitrary decision on the part of the analyst.

Methods and procedures for converting echocardiographic image boundaries to an analog signal with a sonic or light pen have been useful but complex(7). One desirable requirement for effective echocardiovascular research is to have available the capability for producing instantaneous analog signals from echo profiles of cardiac structures on a continuous beat-by-beat basis.

It is the major purpose of this paper to present a working design of a signal processor for a single plane time-motion echocardiographic system as a means of converting echo patterns of two ventricular boundaries simultaneously to analog signals for the purpose of estimating stroke volume and determining cardiac output. The substance of this presentation will be to describe: a) the specific modifications made to existing conventional echocardiographic equipment, b) the interface design required for synchronous operation, and c) the pilot studies upon which the system operation was evaluated.

## SYSTEM DESIGN

A signal processor has been designed as a means for converting video echocardiographic images of cardiac structures into equivalent analog signals for ease of analysis and processing. It was the purpose of this design to utilize the echocardiographic image-to-analog conversion processor to provide for the capability of identifying and converting two cardiac images (near and far) simultaneously, specifically for estimating stroke volume and computing cardiac output from the image-to-analog converted anterior and posterior ventricular wall echo boundaries.

The system design is based on a modified Smith Kline Instruments SKI-20 Echocardiograph which operates at a frequency of 2.25 Mhz with an output power of 10 milliwatts, utilizing focused and unfocused transducers (Aerotech) with a single time-analog module. Specific modifications of the original time-analog module involve the peak envelope detector and range-gate synchronization. The purpose for these modifications was to improve the analog signal quality of the envelope detector output by significantly reducing the internally generated artifact inherent in the original time analog system.

The original peak envelope detector was replaced with a Paynter envelope detector coupled to a low-pass filter network. The Paynter envelope detector operates with a time constant of 5 milliseconds, permitting nearly instantaneous tracking of the near and far (video) targets. The frequency response of the envelope detector was flat from D.C. to 3 megahertz (3 db) with a 12 db per octave roll off. The low-pass filter was a 3-pole Butterworth design with a frequency response flat from D.C. to 100 hertz (3 db) with a 12 db octave roll off.

These specific modifications were performed on two off-the-shelf time-analog modules. The two modified time-analog modules were combined in a way to permit selective and synchronous range-gating of near and far echocardiographic video targets (Figure 1).

Functionally, the transmit pulse A (Figure 2), triggers a monostable Q-1 (Figure 1), resulting in pulse B, the length of which may be adjusted to coincide with the maximum duration of the transducer artifact. The output of Q-1, pulse B, is then differentiated to produce pulse C, and diode clipped and inverted to produce pulse D; a trailing edge of which enables the near-depth range-gate. The near-depth range-gate is then positioned in range and adjusted in width (depth) to coincide with the maximum motion of the near target. The output of the near-depth range-gate, pulse E. The inter-channel inverter functions to provide a trigger between the near and far range-gates which synchronizes the near and far time-analog modules. The trailing edge of pulse B, provides a new trigger for the second

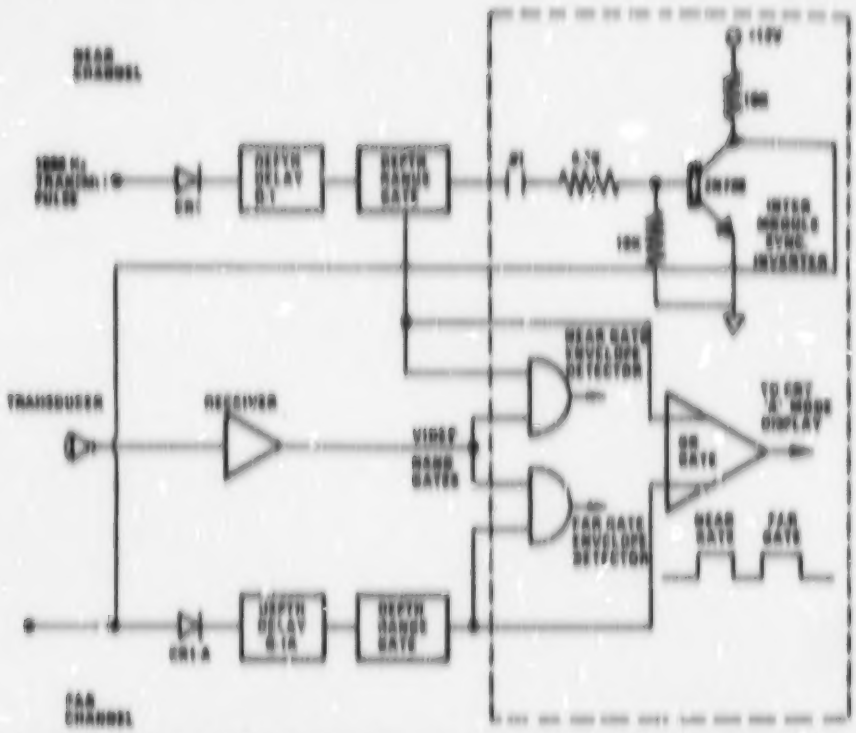


Figure 1. Functional block diagram of the dual time analog echocardiographic signal processing system. The modifications of the basic time analog modules are outlined by the dashed lines.

timr-analog module and enables Q-1A, the delay monostable of the far-depth range-gate, producing pulse H. The output delay monostable Q-1A (pulse H) is adjusted in range so that the trailing edge is within the far range target area. This pulse is differentiated to produce pulse I, diode clipped and inverted to produce pulse J, providing a trigger which in turn enables the far-depth range-gate and produces pulse K. The timing logic of A through E and H through J (Figure 2) is basic to the functional characteristic of each time-analog module. In addition, modification of the basic time-analog module was necessary to provide a differentiated output of the near-depth range-gate E, and the trailing edge G, as part of the inverter inter-channel synchronization process. This procedure is essential for the generation of the near and far range-gates simultaneously.

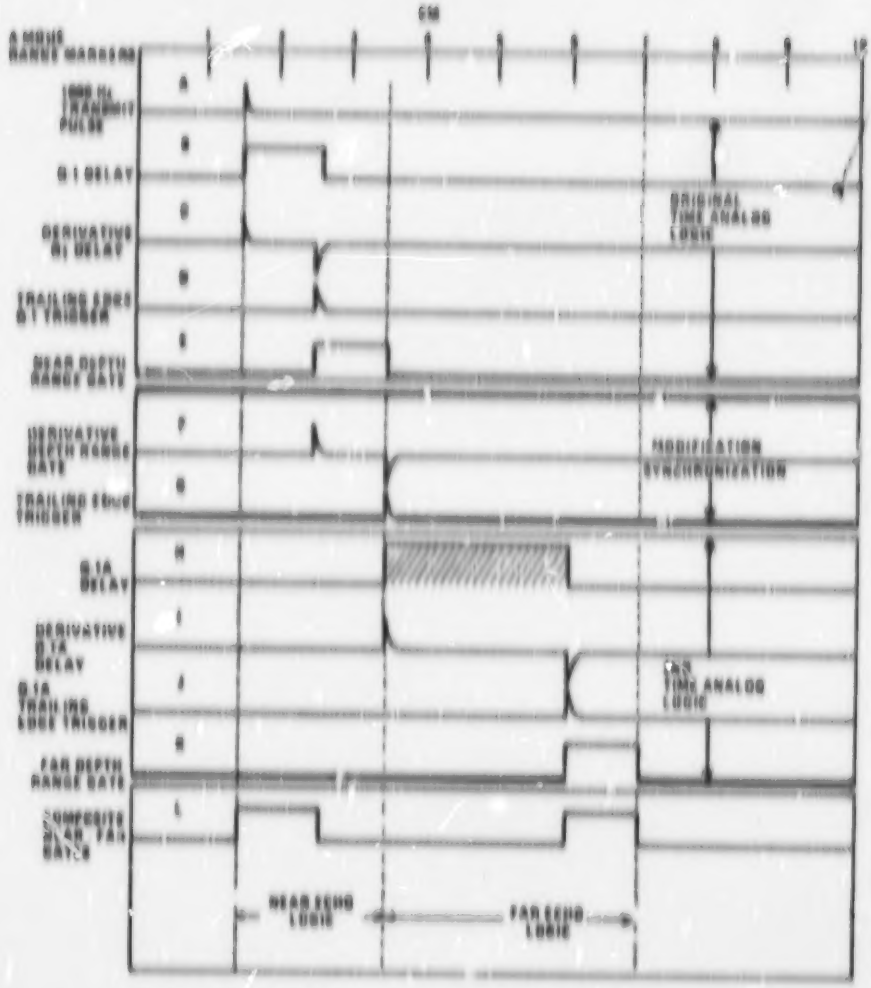


Figure 2. Timing logic for the dual channel analog echocardiographic processing system.

The output of each near- and far-depth range-gates serve as the inputs to an "OR" gate (Figure 1), the output of which is displayed on the cathode ray tube in the A-Mode. This results in a composite signal display on the cathode ray tube consisting of near- and far-depth range-gate outputs superimposed on the existing conventional A-Mode video echos (Figure 3).

Figure 3. Near and far depth range gates positioned over the left ventricular anterior and posterior walls in the A-Mode.

The outputs of the near- and far-depth range-gates also serve as input signals to the video "AND" gates providing only gated echo boundary signals to the envelope detector and low-pass filter for final signal processing and conversion into two near and far analog boundary signals (Figures 1 and 4).

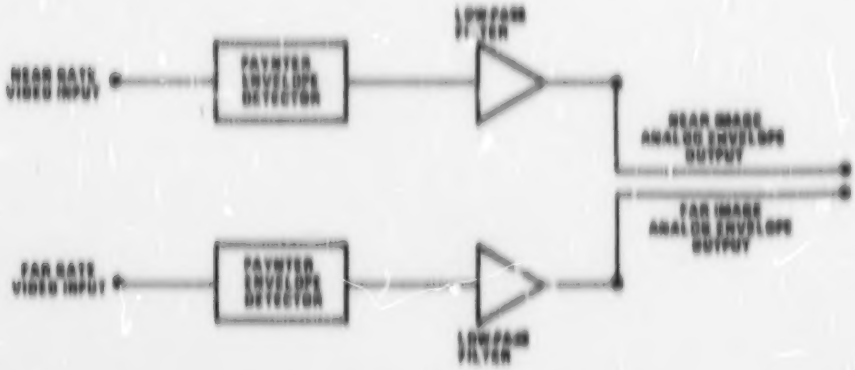
NEAR GATE VIDEO INPUT
PEAKTER ENVELOPE DETECTOR
NEAR IMAGE ANALOG ENVELOPE OUTPUT
FAR GATE VIDEO INPUT
PEAKTER ENVELOPE DETECTOR
FAR IMAGE ANALOG ENVELOPE OUTPUT

Figure 4. The envelope detector and low pass filter.

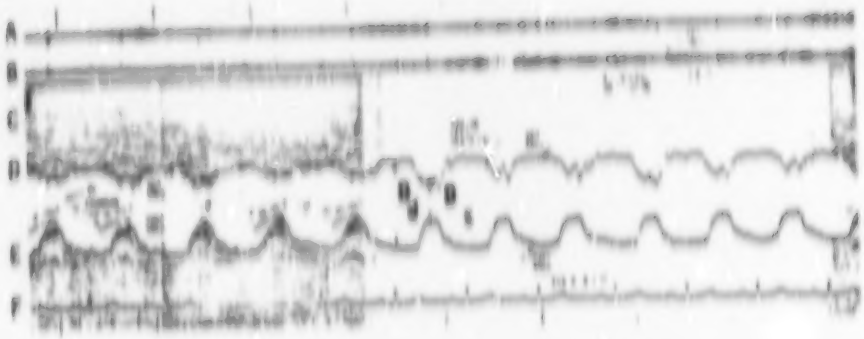


Figure 5. (A) and (B) heart sounds, (C) conventional echo display (D) and (E) analog profile of anterior/posterior walls of left ventricle (F) ECG.

In actual practice, the near and far echos are viewed in the A-Mode. The transducer damping and gain controls are adjusted to enhance the near and the far echo to be range-gated. The near-depth range-gate is manually positioned and superimposed over the near echo and the width (depth) adjusted to encompass the range of motion. Once the near-depth range-gate is adjusted, the far-depth range-gate is manually positioned and superimposed over the far echo and the width (depth) adjusted to encompass the range of motion. At this point, the CRT displays (in the A-Mode) the output of each range-gate (near and far), superimposed on the echocardiographic image which includes echos from the selected near and far targets (Figure 3). Each selected target falls within the width of its respective range-gate. The system control is then switched to the B-Mode display (on the graphic recorder). Then the position and gain controls for the analog boundary signals are manually adjusted so that they are superimposed over the boundary of the B-Mode video images, corresponding to the near and far targets. In this particular application, the product of this effort is two analog signals which correspond to the motion of the left ventricular anterior and posterior wall boundaries (Figure 5). The graphic analysis of this analog output is then performed for the estimation of ventricular stroke volume and computation of cardiac output.

## APPLICATION

A pilot study was conducted based on six healthy male subjects (age range from 22 to 31) who were examined for the purpose of determining the feasibility of estimating left ventricular stroke volume and computing cardiac output based on two echocardiographic

techniques; one based on the analysis of the conventional video image in the M-Mode, and the other based on the analog technique described in this presentation. The study was conducted with the subject in a supine position with the head and shoulders elevated to the horizontal approximately 15 degrees. A standard electrocardiogram was taken on each subject for the purpose of providing a time reference for identifying the diastolic and systolic events of the cardiac cycle. The modified echocardiographic instrumentation* (with output power of 10 milliwatts) and 2.25 MHz transducer** (2.0" diameter unfocused) was calibrated with a standard plastic test block supplied by the manufacturer for the purpose of establishing calibrated depth in the A-Mode.

The transducer was placed in the left parasternal position between the third and fourth intercostal space. A standard arc scan view with the transducer was performed until the anterior and posterior wall of the left ventricle was clearly identified. All measurements, calculations and comparisons were made with the transducer fixed in the left ventricular view position. A conventional echocardiographic record was then taken on each subject in the M-Mode. The near and far range-gates were positioned to correspond to the anterior and posterior ventricular wall echos and adjusted in width to encompass the range of motion of each boundary for further processing and conversion into respective analog signals. The analog output of the echocardiographic processor was positioned (in the M-Mode) to superimpose each analog boundary signal over its corresponding video image. The display of each analog boundary signal alone and in combination with the echocardiographic video image is shown in Figure 5. This display option is accomplished by reducing the video threshold level in the graphic recorder to eliminate the video image from the M-Mode display, while retaining it for the depth range-gate processor.

An M-Mode oscillographic tracing of the combination echocardiographic video image and analog envelope was obtained for analysis. Each oscillographic record on each subject was analyzed for stroke volume and cardiac output based on the following equations(4):

$$SV = D_d^3 - D_s^3, \qquad (1)$$

where, SV = stroke volume (ml), $D_d$ = diastolic dimension (cm), and $D_s$ = systolic dimension (cm), and:

$$CO = SV \times HR, \qquad (2)$$

where, CO = cardiac output (liters/min), and HR (beats/min) = heart rate (determined from the R-to-R interval).

* Smith Kline Instruments/SKI-20
**Aerotech

For the purpose of comparing the systolic end diastolic dimensions extracted from oscillographic tracings corresponding to the conventional video echo and the analog boundary signals, an estimation of stroke volume and cardiac output from each subject was computed using equations 1 and 2 and tabulated (Table 1).

Table 1. Echocardiographic Estimates of Left Ventricular Stroke Volume and Cardiac Output

| | CONVENTIONAL ECHO | ANALOG PROCESSED ECHO |
|---|---|---|
| Subject # | STROKE VOLUME (ml) | STROKE VOLUME (ml) |
| 1 | 55 | 55 |
| 2 | 52 | 51 |
| 3 | 56 | 55 |
| 4 | 62 | 60 |
| 5 | 125 | 134 |
| 6 | 88 | 77 |
| | CARDIAC OUTPUT (liters/min) | CARDIAC OUTPUT (liters/min) |
| 1 | 4.2 | 4.2 |
| 2 | 3.9 | 3.8 |
| 3 | 4.3 | 3.9 |
| 4 | 4.9 | 4.8 |
| 5 | 9.1 | 9.7 |
| 6 | 6.9 | 5.4 |

## DISCUSSION

The analog echocardiogram processor described in this presentation has demonstrated the feasibility of range-gating two simultaneous ventricular echos separated in depth, and converting their respective complex videos to analog signals (in the M-Mode) corresponding to the motion of the anterior and posterior ventricular wall boundaries. The design presented here and its implementation provides an alternate means of performing analyses of echocardiographic signals on a beat-by-beat basis, including digital computer processing. Provision for automatic digital computer processing is not included in the current design; however the analog signals produced from the present system are easily digitized for this purpose. Implementation of a more complete data processing system is being undertaken in combination with a microprocessor and will be the subject of a future report.

The position and depth adjustments of each range-gate is performed manually. This adjustment procedure is tedious and cumbersome. In addition, the ability for the analog to track the video image with excellent fidelity is not possible. A noticeable phase shift or tracking error may be detected when the echo image and analog envelope signal are superimposed (Figure 5). Provisions are being made to correct for some of these inconveniences by providing for an automatic range-gate tracking feature utilizing the same microprocessor currently scheduled to perform the automatic data processing function. At the present time, the manual method is simple and reliable, but frustratingly slow. In addition, part of the phase shift error is being corrected by using logrithmic amplifiers and digital filtering techniques.

The application of the analog echocardiogram processor is not limited to ventricular measurements alone. Depending on the echos to be analyzed, it is possible to range-gate other structures such as the anterior and posterior walls of the aorta(8), aortic valves, mitral valves and convert the gated motion of these structures to analog boundary signals for further analysis of cardiac performance.

At the present time the authors have undertaken a further study which involves the use of a microprocessor to perform computations, coordinate the timing logic and provide for the automatic range-gate tracking function. The substance of this study will be reported at a future date.

## CONCLUSIONS

This study has demonstrated the practicality of redesigning a conventional echocardiograph to provide for more than one time analog signal from a single transducer. Specifically, this redesigned system provides two simultaneous analog signals corresponding to the near and far boundary echos of a complex echocardiographic ventricular image from which stroke volume and cardiac output was estimated. The analog echocardiographic method compares favorably with the conventional echo image method for this determination. This system of echocardiographic processing and signal analysis for evaluating dynamic cardiac changes without the loss of conventional echocardiographic information enhances the ease of signal analysis.

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